# Direct Measurement of Supernova Neutrino Emission Parameters with a Gadolinium-Enhanced Super-Kamiokande Detector

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The time-integrated luminosity and average energy of the neutrino emission spectrum are essential diagnostics of core-collapse supernovae. The SN 1987A electron antineutrino observations by the Kamiokande-II and IMB detectors are only roughly consistent with each other and theory. Using new measurements of the star formation rate history, we reinterpret the Super-Kamiokande upper bound on the electron antineutrino flux from all past supernovae as an excluded region in neutrino emission parameter space. A gadolinium-enhanced Super-Kamiokande should be able to jointly measure these parameters, and a future megaton-scale detector would enable precision studies.

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When a massive star dies, its core collapses and rebounds, producing an outgoing shock wave that should eject the stellar envelope, causing the optical supernova, and leaving behind a neutron star remnant. However, in simulations, the shock wave stalls, leading to the whole star collapsing into a black hole, failing to produce an optical supernova or spread its heavy-element yields [1]. Since the required explosion energy is only $\sim 1\%$ of the emergent neutrino energy, a full accounting of the neutrino emission is essential for understanding supernovae. Further, in the Bethe-Wilson delayed explosion model, the neutrinos revive the shock [2]. Resolution of the supernova problem would also have profound implications for the history of stellar evolution and nucleosynthesis.

The weak interactions of neutrinos, which allow them to reveal the dynamics deep within the exploding star, also make their detection challenging. The last nearby supernova, SN 1987A, occurred in the Large Magellanic Cloud at 50 kpc, and $\simeq 20$ neutrinos were detected [3] preceding the optical supernova, confirming our basic understanding of the explosion [4]. However, even taking into account the small statistics, the fitted ranges for the time-integrated luminosity and average energy are perplexing, showing clear discrepancies among the experimental detections and theory [5, 6]. A Milky Way supernova would yield many events in present detectors, but the expected supernova rate is only $\sim 3$ per century. We have shown that with proposed megaton-scale detectors, it will be possible to build up the spectrum by detecting neutrinos one or two at a time from supernovae within 10 Mpc, at a rate as large as $\sim 1$ neutrino per year [7].

Here we propose a new approach, which could begin immediately, if the existing Super-Kamiokande (SK) detector were modified by the addition of gadolinium to greatly reduce backgrounds, as proposed by Beacom and Vagins [8, 9]. We consider the spectrum of the Diffuse Supernova Neutrino Background (DSNB) [10, 11, 12, 13] as the observable. The DSNB predictions depend on the redshift evolution of the supernova rate, which is separately measurable and increasingly well known, and the

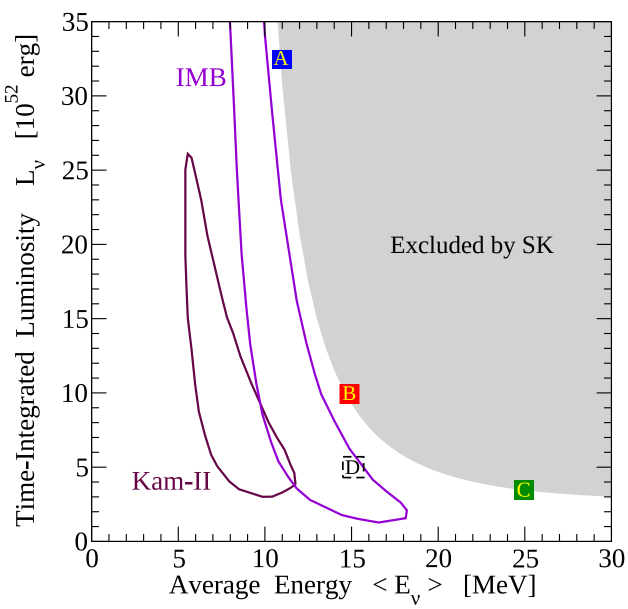


FIG. 1: (Color online) Joint limits on the time-integrated luminosity $L_\nu$ and the spectrum average energy $\langle E_\nu \rangle$ for electron antineutrinos. The two contours are the allowed regions at 90% C.L. from the SN 1987A analysis of Ref. [5] and our shaded region corresponds to the SK 90% C.L. upper limit on the DSNB flux [16].

neutrino emission per supernova, the object of our study. While the received neutrino spectrum will be redshifted, it will have relatively high statistics, up to several events per year in SK. Recently, the DSNB uncertainties from the star formation rate history [14, 15] narrowed enough that it is now sensible to reinterpret the SK flux limit [16] as an exclusion region in the plane of the time-integrated luminosity and average energy, which can be directly compared to the allowed regions from SN 1987A. Anticipating further improvements in the astronomical data, we show that a gadolinium-enhanced SK should be able to usefully constrain the emission parameters in much of the interesting range.

**Supernova 1987A Signal.**—One of the triumphs of astrophysics, nuclear physics and particle physics was the detection of neutrinos from SN 1987A, so far the only astrophysical source besides the Sun seen with neutrinos. The $\simeq 20$ events in the Kamiokande-II (Kam-II) and IMB detectors are assumed to be mostly inverse beta events, $\bar{\nu}_e + p \rightarrow e^+ + n$; the cross section $\sigma \sim E_\nu^2$, with the positron carrying nearly the full neutrino energy [17]. The number of detected events $N_{det} \sim (L_\nu/\langle E_\nu \rangle) \cdot \langle E_\nu \rangle^2 \sim L_\nu \cdot \langle E_\nu \rangle$, where $L_\nu$ is the time-integrated luminosity of the electron antineutrinos and $\langle E_\nu \rangle$ is the average energy of the neutrino emission spectrum. The average detected energy $\langle E_{det} \rangle \sim \langle E_\nu \rangle$. The combination of these two constraints explains the banana-shaped allowed regions shown in Fig. 1, taken from the full spectrum analysis of Ref. [5] (those authors assumed a Maxwell-Boltzmann thermal emission spectrum). We show only the 90% C.L., which is appropriate for this level of precision, to avoid cluttering the figures.

At least three puzzling features of the SN 1987A data still stand out. First, the fits to the Kam-II and IMB data for the neutrino emission parameters barely overlap, due to the disagreement on the spectra [5, 6]. Second, the results disagree with the canonical expectations [5, 6], conservatively indicated by point **D** in Fig. 1. This corresponds to a neutron star binding energy of $3 \times 10^{53}$ erg, assumed shared equally among the six flavors, and an effective received $\bar{\nu}_e$ temperature of about 5 MeV. Both the Kam-II and IMB data allow very high luminosities, perhaps reflecting a larger neutron star binding energy and/or a violation of its assumed equipartition among flavors. Both, but especially Kam-II, allow very low average energies, especially if neutrino mixing with higher-temperature flavors is taken into account (i.e., with temperatures possibly as large as 8 MeV). Third, both the Kam-II and IMB results are in significant disagreement with model-independent tests of the angular distributions of the detected events [17, 18, 20].

We emphasize that the Kam-II and IMB results are *roughly* consistent with each other and theory; still, there are puzzling issues raised which cannot be answered without new data. Also, all supernovae may not be alike, and the DSNB results will reveal the *average* neutrino emission parameters of supernovae, possibly more relevant for cosmological applications. We therefore stress that the adoption of SN 1987A as a template for DSNB studies is undesirable.

**SK DSNB Limit.**—To predict the DSNB flux, one needs only the core-collapse supernova rate as a function of redshift $z$, convolved with the neutrino emission per supernova, taking into account redshift effects [10, 11, 12, 13]. At present, the former is calculated from the measured star formation rate and the stellar initial mass function, which determines the fraction of stars that end their lives as core-collapse supernovae. We base our results primarily on the GALEX star formation rate data [14], for which the normalization uncertainty is now at the $\simeq 30\%$ level. This yields results similar to those of the Concordance Model of Ref. [13], which was shown to be consistent with the latest measured star formation, thermonuclear (type Ia) supernova, and core-collapse supernova (types II, Ib, and Ic) rates, as well as other data, and which predicts a DSNB flux just below the present SK limit. (See also the more recent Ref. [15].) The DSNB prediction thus depends first on a purely astronomical factor, which is already measured well and will ultimately be precisely and unambiguously measured through direct data on the supernova rate versus redshift (note that optically failed supernovae with substantial neutrino emission would increase the core-collapse rate) [13]. The second factor, the average neutrino emission per supernova, must be measured directly, and this is our focus.

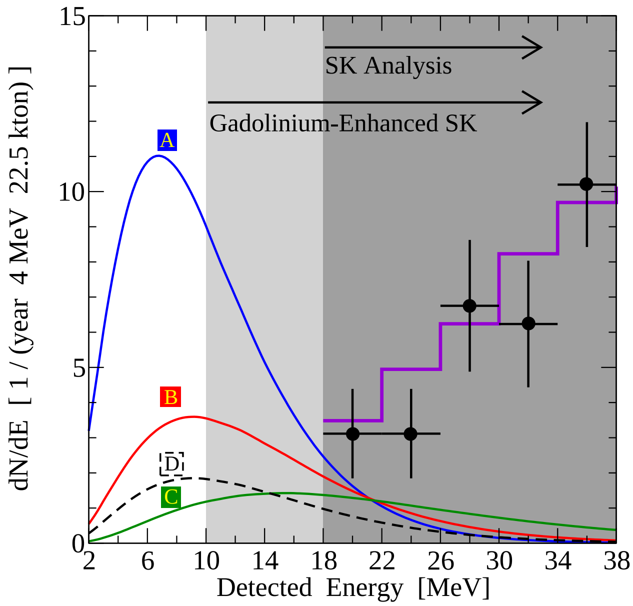


FIG. 2: (Color online) DSNB detection spectra for selected parameters (solid and dashed curves), efficiency-corrected SK data (points with error bars), and detector background (solid steps), all in counts per 4 MeV, per year, per SK fiducial volume. The values for the representative points **A**, **B**, **C** and **D** are given in Table I. SK is so far sensitive only to the dark shaded region above 18 MeV due to high backgrounds at lower energies (not shown). With the addition of gadolinium, these backgrounds in the range 10–18 MeV would be removed, and that shown reduced by a factor $\sim 5$, opening up also the light shaded region for analysis [8, 9].

In 2002, SK reported their DSNB flux upper limit for electron antineutrinos with a detection energy threshold of 18 MeV as 1.2 cm$^{-2}$ s$^{-1}$ (90% C.L) through non-detection of excess counts above background fluctuations [16]. Due to the rising background and falling signal with increasing energy, almost all of the statistical power derives from the first two bins in Fig. 2, which is why the SK flux limit was the same for DSNB models with different spectral shapes. With the present statistics, it is enough to use just these two bins to limit the signal, noting that the other bins fix the background normaliza-

TABLE I: The values for the points **A**, **B**, **C** (near the SK upper bound) and **D** (canonical values) of the figures.

| Point | $\langle E_\nu \rangle$ [MeV] | $L_\nu$ [$10^{52}$ erg] | Sensitivity |
|---|---|---|---|
| **A** | 11 | 32 | Average Energy |
| **B** | 15 | 10 | Both Variables |
| **C** | 25 | 3.5 | Integrated Luminosity |
| **D** | 15 | 5 | Lowered Sensitivity |

tion. While at the time of the SK analysis, the DSNB models differed significantly in their normalization, the latest astronomical data greatly restricts this freedom, and will eventually eliminate it, modulo the differences in neutrino emission per supernova that we want to test. Thus it now makes sense to reinterpret the SK event rate limit ($\simeq 2$ yr$^{-1}$ in 18–26 MeV [16]) in terms of the supernova electron antineutrino emission parameters, the time-integrated luminosity and average energy. The result of our analysis is that the shaded region in Fig. 1 is excluded. (We assumed a thermal emission spectrum of the form used in Ref. [6], taking $\alpha = 3$, which corresponds to a somewhat "pinched" spectrum.) This does not yet reach the allowed regions deduced from the SN 1987A data, but it is encouragingly close. Neutrino mixing can blend the initial $\bar{\nu}_e$ spectrum with higher-energy $\bar{\nu}_\mu/\bar{\nu}_\tau$ spectra. We are limiting an effective composite spectrum, which will be dominated by the harder spectrum [10]. Thus our analysis is conservative, in that with neutrino mixing, the interpretation of the DSNB bound would be more constraining (e.g., Ref. [13]).

Beyond the two supernova neutrino emission parameters used here, there is also the question of the spectrum shape, and whether it is distorted from thermal by being "pinched" or "anti-pinched" [6]. The SK energy threshold of 18 MeV is used in Ref. [16] is high, especially noting that redshifts $z \lesssim 1$ are relevant; the SK limit is thus based on energies $\simeq 20 - 40$ MeV in emission, where the spectrum uncertainties are largest. Indeed, this is part of the motivation for lowering the SK energy threshold, so that the detected events would correspond to emission from the better-understood spectrum peak region.

One can get more insight by examining three points, **A**, **B**, and **C**, shown in Fig. 1 and Table I, which are at the edge of detectability. We also consider a point **D**, which is often regarded as the canonical values for $\bar{\nu}_e$ emission before neutrino mixing. The DSNB spectra for these points are shown in Fig. 2, together with the SK data and background expectations (dominantly from the decays of sub-Čerenkov muons produced by atmospheric neutrinos). The three points **A**, **B**, and **C** correspond to almost equal yields (comparable to the fluctuations in the backgrounds) in 18–26 MeV, where the present SK sensitivity is greatest. The point **D** produces fewer signal events and is safely allowed. Note that these spectra are quite different at lower energies. Thus it is clear that in order to make the necessary progress over the

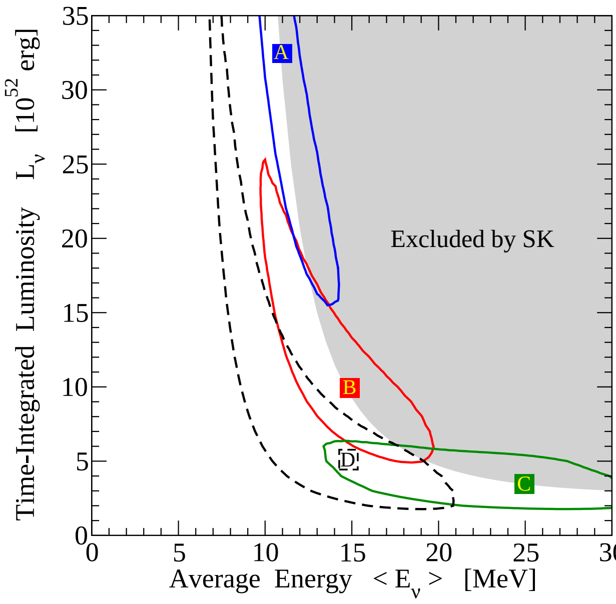


FIG. 3: (Color online) Possible 90% C.L. measurements of the emission parameters of supernova electron antineutrino emission after 5 years running of a gadolinium-enhanced SK detector.

present background-limited search, SK must reduce both the background rates and the energy threshold.

The points **A**, **B**, and **C**, besides representing three very different possibilities, are also the most favorable for being probed by SK in the near term. (Below, we discuss the outlook for models with a lower neutrino emission per supernova.) These points are chosen just with respect to what is allowed by the DSNB, deliberately not taking into account other possible constraints, so that the impact of our results can be clearly seen. Additionally, it is important to keep an open mind about what the true parameters are, given that (a) numerical supernova models fail to explode [1], and (b) it remains possible that SN 1987A was very different from an average supernova.

Points **A** and **C** are relatively extreme, compared to the more canonical point **D**. However, possibilities like **A** might occur if the neutron star binding energy and the fraction of this energy carried away by $\bar{\nu}_e$ (i.e., a violation of the usually assumed equipartition of the energy among the six flavors) are both larger than expected [1]; more directly, **A** is very close to part of the IMB allowed region for the SN 1987A data. Possibilities like **C** correspond to a temperature of about 8 MeV, which is within the range considered in many papers, especially if neutrino mixing is taken into account.

**Gadolinium-Enhanced SK Sensitivity.**—In SK, DSNB $\bar{\nu}_e$ would be detected by the inverse beta reaction $\bar{\nu}_e + p \to e^+ + n$ on free protons [17]. At present, this is a (positron) singles search, for which there are very large background rates [16]. With dissolved gadolinium, SK could also detect the neutron via its radiative capture ($\Sigma E_\gamma \simeq 8$ MeV), which would give a tight temporal

and spatial coincidence for the signal events [8, 9]. This would reduce the sub-Čerenkov muon decay background shown in Fig. 2 by a factor $\sim 5$, and would remove the spallation backgrounds in the range 10–18 MeV; below about 10 MeV, the reactor $\bar{\nu}_e$ signal suddenly becomes dominant [8, 9]. We emphasize that SK would be working well within its design range when detecting these positrons and neutron captures, i.e., at these energies the detection efficiency is very high, nearly constant, and well-measured through calibrations. In contrast, in the detection of neutrinos from SN 1987A, both Kam-II and especially IMB had events detected at energies where the efficiency was low and/or varying quickly [3].

Besides increasing the signal rate and improving the ability to test the DSNB spectral shape, the capability for neutron tagging could allow a rate-limited, instead of background-limited, search, so that the sensitivity could improve linearly with detector exposure. To examine the prospects for a gadolinium-enhanced SK, we again consider the four points in Table I. For each, we simulate the expected neutrino spectra over a 5-year period (i.e., 5 times the yields shown in Fig. 2, noting the background reduction). We fit the spectra of DSNB and background events simultaneously, and compute the $\chi^2$ in 4-MeV bins, as in Ref. [16]. With these statistics, the Gaussian $\chi^2$ is adequate to draw the 90% C.L. contours.

In Fig. 3, we show the expected determinations of the physical parameters at 90% C.L. The spectra corresponding to **A**, **B**, and **C**, while presently indistinguishable above 18 MeV, would be clearly separable in a gadolinium-enhanced SK (see Fig. 2). With a lower energy threshold, there is greater sensitivity to both the time-integrated luminosity and average energy through the spectral shape as well as normalization. At different points, the relative sensitivity to the two parameters changes, as listed in Table I and shown in Figs. 2 and 3. If we allowed the supernova rate history to be free, then the normalization of the supernova rate would be degenerate with the time-integrated luminosity, while the rate of increase with redshift would be degenerate with the average energy. Thus near point **A**, inaccuracies in the normalization would have little impact, and likewise near point **C** for inaccuracies in the rate of increase with redshift. While we think that the supernova rate uncertainties will play a minor role compared to those on the supernova emission parameters, this may make the determination of one variable more robust than the other.

If the true parameters, even taking neutrino mixing into account, are closer to the canonical values (point **D**), then the detection rate will be lower, and hence the allowed region larger. (From the size and shape of this contour relative to the others, one can estimate how the contours for other points would look.) Even in the case of point **D**, in 5 years a gadolinium-enhanced SK would detect $\simeq 15$ events, comparable to the SN 1987A yield, which should help distinguish between the Kam-II and IMB solutions. If the Kam-II region is correct, then the detection rate will be even lower; note that an outcome that disfavored the IMB region might be viewed as selecting the Kam-II region, given the prior information from SN 1987A. If the supernova neutrino emission parameters are both low, a megaton-scale detector may be necessary to accumulate good statistics.

**Discussion.**—The $\simeq 20$ neutrinos from SN 1987A provided a rough confirmation of core-collapse supernova neutrino emission, and hence of the dynamics of the exploding star in the first several seconds after collapse. These details of core-collapse events will forever remain invisible with photons, but can be revealed by neutrinos, if they can be detected. While very challenging, it is hard to overstate the importance of this goal. Since nearly 20 years after SN 1987A, we have no further *direct* information on supernova neutrino emission, techniques besides waiting for a Milky Way supernova must be considered.

We propose that with the rapidly improving precision of the astronomical data, it will be possible to use measurements of the DSNB to constrain the $\bar{\nu}_e$ emission per supernova. This information will be limited, in that neither the dynamic timescales nor the emission in the other neutrino flavors can be measured; only a Milky Way supernova can provide those data. However, even with just $\bar{\nu}_e$, the time-integrated luminosity and average energy will constrain the explosion energy and proto-neutron star opacity, especially if reasonable assumptions are made about the other flavors. Despite these caveats, and the limited statistics, we stress that this technique is unique in that in a very short time it could begin providing steadily better clues to the mysteries of SN 1987A.

Our results in Fig. 3 show that a gadolinium-enhanced SK detector would have useful sensitivity to an interesting range of supernova emission parameters. The recognition that the astrophysical uncertainties are small and quickly diminishing allowed us to reinterpret the SK flux constraint [16] in terms of the neutrino emission per supernova. As a practical matter, we encourage SK to represent future results in this way, as it is more directly connected to the measured event spectrum than the integral of the flux above a given energy (in particular, since the latter does not contain the important weighting by the detection cross section), i.e., is less model-dependent.

If a Milky Way supernova is detected, this would *increase* the value of the proposed DSNB measurement. The comparison of results could probe whether the neutrino emission from core-collapse supernovae is as uniform as presently assumed. Alternatively, it could test the measured core-collapse rate history [12], and whether there is an additional neutrino background from explosions which fail [13], emitting neutrinos but not creating an optical supernova, just as is seen in simulations [1].

Proposed megaton-scale detectors would greatly extend the sensitivity to these and more general spectra, and could bring precision to the measurement, due to the very high DSNB statistics. Such detectors could also allow the accumulation of events from identified supernovae within 10 Mpc [7]. While the statistics of the latter would be relatively lower, that spectrum would not be

redshifted, nor dependent on the evolution of the cosmic supernova rate, and hence would be complementary to the DSNB spectrum.

The neutrino emission per supernova is also important for understanding nucleosynthesis, especially of the heavy elements beyond iron, which are believed to be formed only in core-collapse supernovae, and which require special conditions that may be importantly affected by the neutrinos [21]. In addition, Yoshida *et al.* [22] have recently shown that the yield of the light element $^{11}$B constrains the neutrino emission parameters to be close to the canonical values, which is favorable for confirmation by *direct* detection. Combining the nucleosynthesis results [22] with future sensitivity to the DSNB electron antineutrino flux (as stressed here) [9, 10, 11, 12, 13], the DSNB electron neutrino flux [18, 19], and the summed spectrum of nearby supernovae [7] will provide complementary and restrictive probes of the details of supernova neutrino emission and the history of stellar birth, life, and death.

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